Modeling of SOC-700 Hyperspectral Imagery with the CAMEO-SIM Code

for the Proceedings of the
2007 Ground Systems Modeling, Validation & Testing Conference

Roger Evans
US Army RDECOM-TARDEC
Warren, MI 48397 USA

ABSTRACT

The CAMEO-SIM software program provides a physics-based spectral radiance simulation over the complete range from UV to Far-IR, the only real limitation being one of obtaining the necessary input data. This paper investigates a CAMEO-SIM simulation of the visual and near-IR spectral range measured by the portable Surface Optics SOC-700 hyperspectral sensor. The FOV and spatial resolution of the sensor will also be modeled appropriately. A description of the SOC-700 hardware, the SOC-700 data, the necessary CAMEO-SIM input data, the settings used for CAMEO-SIM, the CAMEO-SIM output, and a comparison of the hypercubes from each will be presented. The comparison will include the application of various hyperspectral analysis algorithms to both real and modeled data.

INTRODUCTION

Spectral and hyperspectral (more than 100 bands) remote sensing have been in use since the 1970's. Recent advancements in the technology have made small, portable systems possible at a reasonable cost. These sensors have become small and light enough to be used in UAVs (unmanned aerial vehicles) and robots. One such portable system is the Surface Optics SOC-700. In parallel with hyperspectral sensor developments, recent modeling codes such as CAMEO-SIM have made it possible to model hyperspectral systems with a good level of fidelity. This paper investigates the modeling of SOC-700 hyperspectral data using CAMEO-SIM.

THE SOC-700 SYSTEM

The SOC-700 system (Figure 1) combines mostly off-the-shelf components with custom software and detailed calibration techniques to produce a portable hyperspectral system at a relatively low cost.

Figure 1 – SOC-700 in the field

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **26 OCT 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Modeling of SOC-700 Hyperspectral Imagery with the CAMEO-SIM Code**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Evans, Roger**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**		8. PERFORMING ORGANIZATION REPORT NUMBER **18184**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM TARDEC** 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **18184**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**19**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This system has a spatial resolution of 640x640 pixels and captures 120 spectral bands. This type of data is often referred to as a "hyperspectral cube", due to its 3-dimensional nature. The capture time is generally 6-8 seconds due to the use of a mirror to scan in the x direction (horizontally). The SOC-700 is available in various spectral bands, our system measures approximately 400 - 900 nm (0.4 – 0.9 micron). This covers the full visual band, and the lower part of the near-IR band. Each cube of SOC-700 data is 94 MB in size and contains calibrated spectral radiance values for each pixel at each wavelength.

THE CAMEO-SIM CODE

The CAMEO-SIM software code from Lockheed Martin Insys in the U.K. provides physics-based modeling of spectral radiance over a wide (0.3 – 25 micron) wavelength range. Materials are characterized using physically meaningful properties, and MODTRAN is used for modeling the sun, sky, and atmospheric transmission. Many rendering programs can create attractive images, but very few can generate physically meaningful results in units such as watts/meter^2/steradian. By setting the response function of a virtual sensor to 100+ bands, CAMEO-SIM can model hyperspectral sensors such as the SOC-700. CAMEO-SIM runs on standard PCs under the Linux operating system.

THE OCEAN OPTICS SPECTROMETER

An important requirement for hyperspectral modeling is to have the necessary spectral reflectance data for the surfaces being modeled over the spectral band of interest. A portable system allows measurement of materials which cannot be taken into a laboratory. The system used to measure the materials for this paper was an Ocean Optics USB-2000 spectrometer, shown in Figure 2. The actual spectrometer component is the small box attached to the laptop computer, as in Figure 3.

Figure 2 – Ocean Optics Fiber Optic Spectrometer with Laptop PC

Figure 3 – Spectrometer Component attached to Laptop PC

This system uses fiber optics to send light to the sample and to return light back to the spectrometer. A Spectralon sample provides a nearly 100% reflective and spectrally flat "white reference", and a dark current subtraction is also performed. This system can measure diffuse reflectance, specular reflectance, total reflectance (using an integrating sphere), transmission, and irradiance. The USB-2000 is available with various spectral bands and resolutions, our system measures 350 to 1024 nm, with approximately 1000 usable data measurements over the band. For this test, the diffuse spectral reflectance of each sample was measured.

HYPERSPECTRAL MODELING WITH CAMEO-SIM

For a first attempt at modeling hyperspectral data with CAMEO-SIM, two simple scenes were measured with the SOC-700 and the USB-2000, and then recreated using CAMEO-SIM. One scene contained the standard Macbeth color calibration chart with 24 color samples, mounted to cardboard. The other scene was the same cardboard piece with 6 actual leaves attached, and also one “artificial leaf”, made of green paper. The leaves used included oak, maple, and red maple, for an interesting spectral variation. The two scenes were measured on the same day at nearly the same time, using the SOC-700 system. The integration time of the sensor was set to avoid saturation on the Spectralon sample. Some saturation on the leaves was unavoidable due to the very high brightness of the glints on the leaves. The measurements were made on a sunny October day with minimal clouds, measurements were only taken when the sun was not behind a cloud. Figures 4 and 5 show the two scenes, using color pictures created by integrating the SOC-700 radiance data against the standard x, y, z color curves and then transformed into RGB values. The cement and grass reflectances were measured outdoors with the USB-2000 spectrometer. The other test items were taken indoors and measured with the same spectrometer.

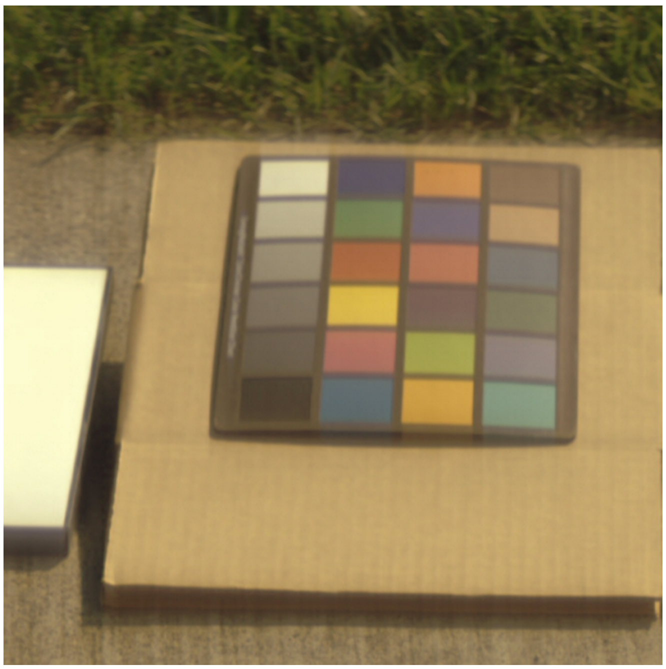

Figure 4 – Scene with Macbeth chart and Spectralon (white panel on the left)

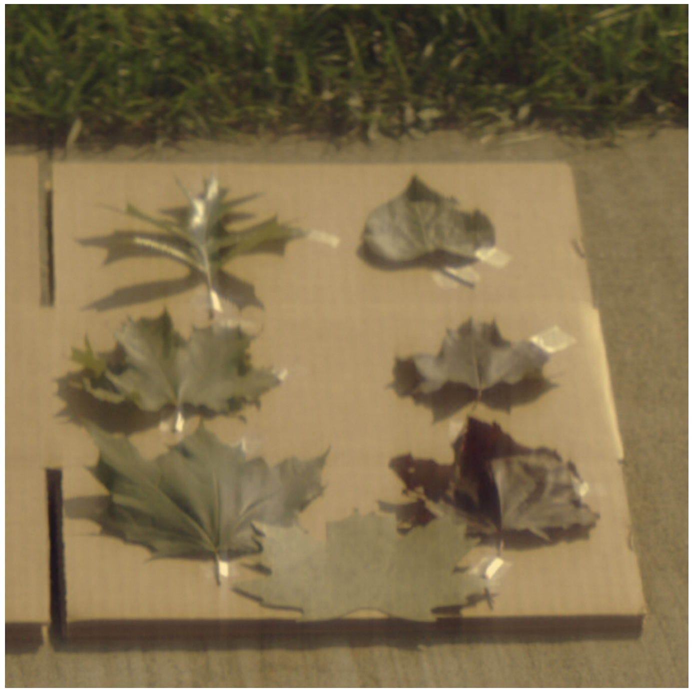

Figure 5 – Scene with Six Real Leaves and One Paper Leaf (at bottom)

Modeling these two scenes required certain inputs in the correct formats for use in the CAMEO-SIM code:

- a faceted geometry of the scene, with separate objects for each material used
- spectral reflectance measurements for each of the materials
- a MODTRAN sun/sky/atmosphere generation run appropriate for the date, location, and time modeled
- response function, resolution, and FOV (field of view) information for the sensor being simulated.

For most CAMEO-SIM modeling, a terrain is also used, matching the terrain of interest. However for these simple scenes no terrain was necessary. So the items were modeled as basically "floating in space", without a terrain.

To generate the scene geometry, Rhino 3.0 software was used. Figure 6 shows a screenshot of the test panel geometry in Rhino. Only a few of the Macbeth samples were assigned render colors for verifying orientation, since these RGB colors have no meaning in the CAMEO-SIM simulation. However, it is a good idea to give all of the objects unique names in Rhino, this is a great help when assigning material properties in CAMEO-SIM (Figure 7). Since the +y axis is considered as north in CAMEO-SIM, after these screenshots were taken the panel and simple background (cement and grass) geometries were rotated 180 degrees around the z axis. Figure 8 shows a simple rendering of the scene. The camera box was not included in the final geometry, although a lens disk was retained to verify the correct virtual camera location in CAMEO-SIM. The Rhino geometry was facetized and exported to the OBJ file format, which then easily imports into CAMEO-SIM.

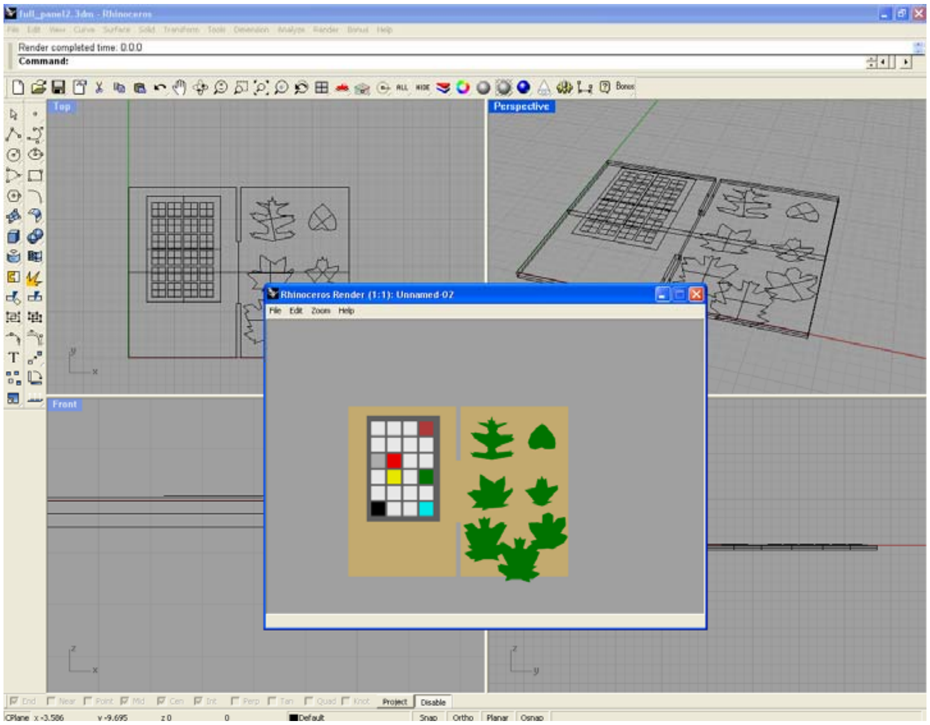

Figure 6 – The Rhino Program used for Scene Generation

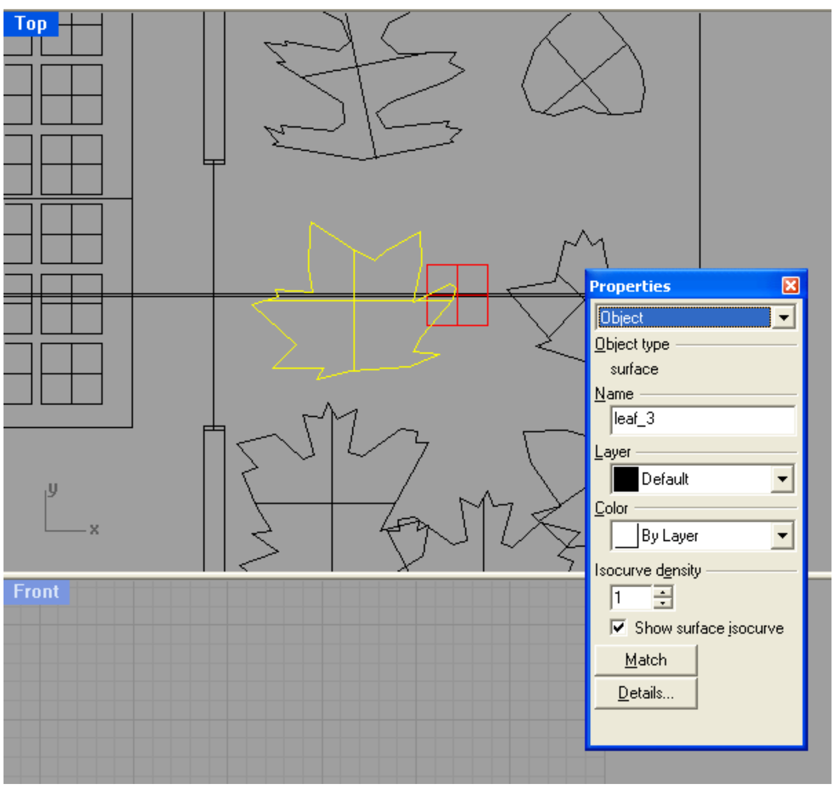

Figure 7 – Assignment of Object Names in Rhino

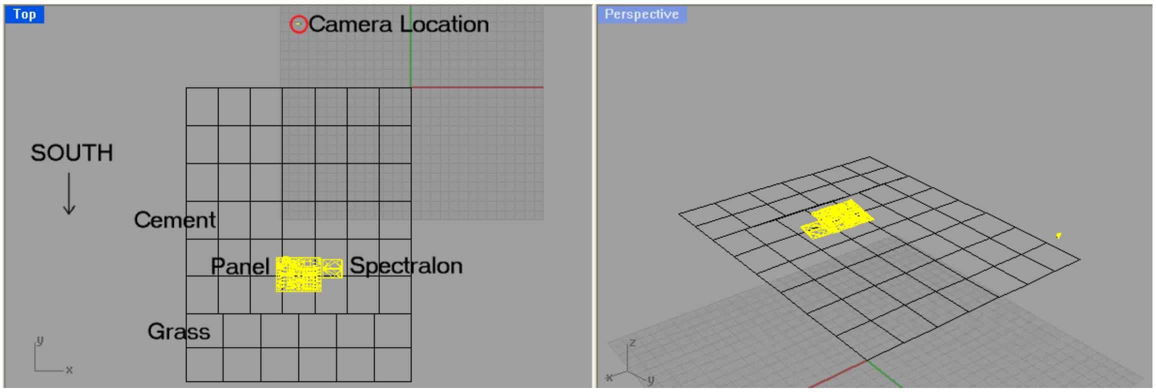

Figure 8 – Full Scene Displayed after Rotation and Facetization

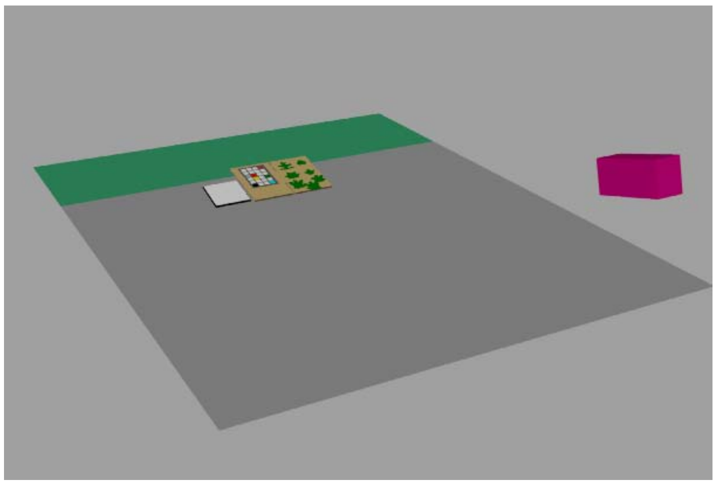

Figure 9 – Full Scene as Rendered with Rhino, the Purple Box is the Virtual Camera Location

The spectral reflectance data for each material came from Ocean Optics USB-2000 measurements. The leaves were measured against the same cardboard backing, to minimize any effects of the leaves being translucent, rather than fully opaque. A simple custom program, shown in Figure 10, converts each measurement into the format required by CAMEO-SIM. This program also allows “trimming off” the noisy spectral data at the high and low ends of the spectrum. However it is important to keep at a minimum the full spectral range of the SOC-700 system, 400 to 900 nm. This software also truncates any noisy values less than 0.0 or greater than 1.0 (100% reflective).

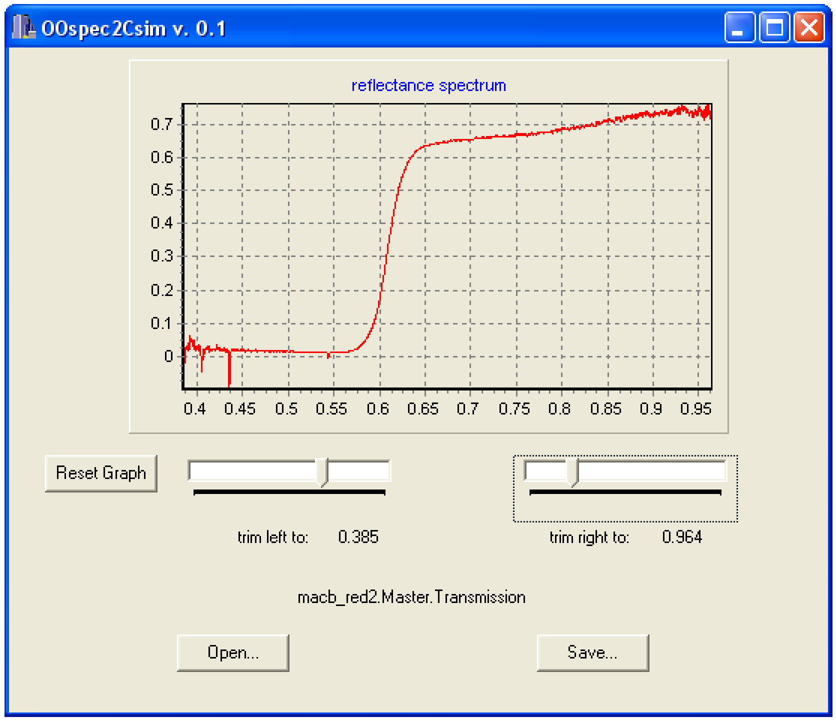

Figure 10 – Spectral File Conversion Software

The MODTRAN code is effectively built into CAMEO-SIM, and is used to generate the sun, sky, and atmospheric absorption information for CAMEO-SIM runs. Since MODTRAN runs can take a large amount of time to complete, this information is pre-computed for a specified 24-hour period. For this test, several MODTRAN runs were computed for the date and location modeled, so the effect of the various settings could be observed. These settings include such items as the season, the haze level, and the generation algorithms used (Figure 11). Figure 12 shows the results of several runs given the same location and time but with other settings varied. The brightness levels vary, but the overall spectral shape showed minimal variation. In any case it is nearly impossible to match a real-world scene exactly, since the real world lighting varies in brightness and spectrum, even over just a few seconds. This variation is usually not detectable by the human eye, except in gross cases (sun going behind a cloud).

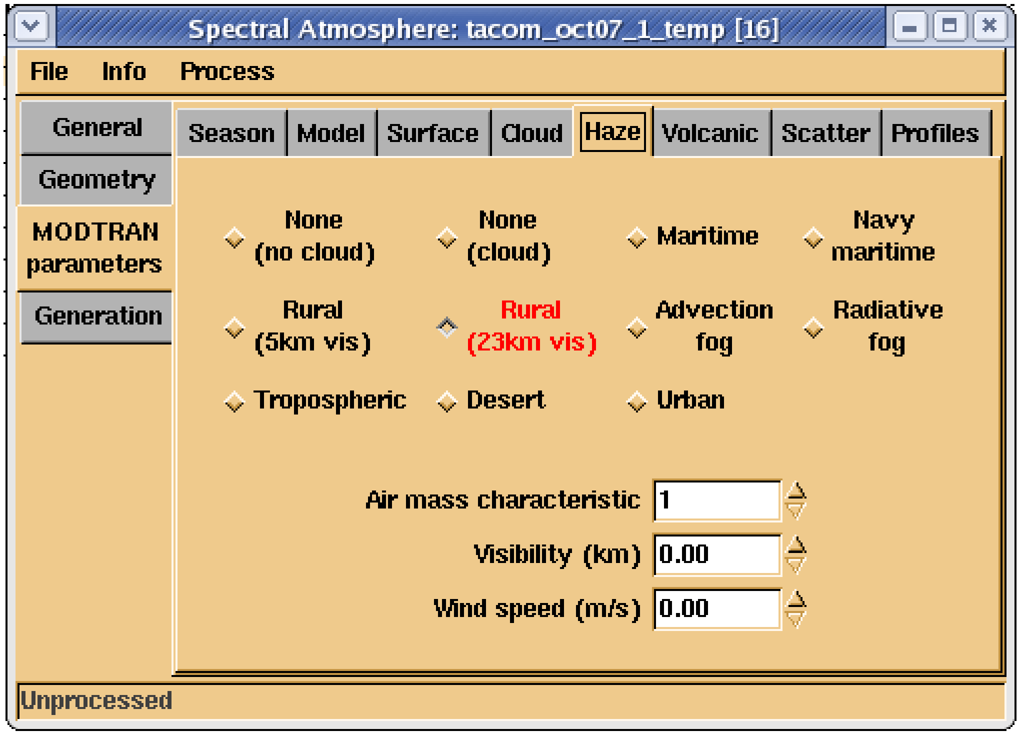

Figure 11 – One of the MODTRAN Settings Screens in CAMEO-SIM

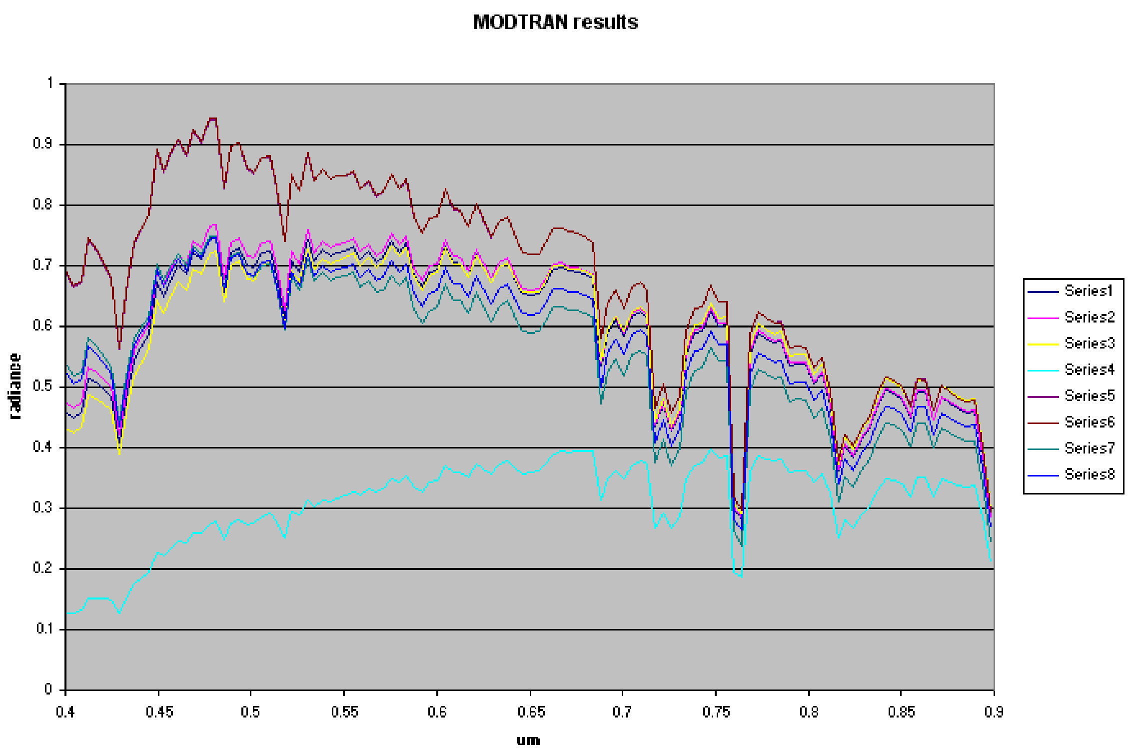

Figure 12 – Modeled Spectral Radiance from the Spectralon Sample using Various MODTRAN Settings

The MODTRAN run selected for this simulation included the following settings:

- Spectral Band : 380 - 900 nm (.380 - .900 um)
- Season : Summer
- Model : Mid-latitude Summer
- Cloud : none
- Haze : Rural (23 km visibility)
- Scatter : Mie
- Multiple Scattering : Isaac model
- Azimuth Dependence : on

Additionally, the latitude and longitude were entered for Detroit, Michigan and the month and date were properly set.

The final piece of the simulation puzzle was to include the various characteristics of the SOC-700 system. Some are easy, such as setting the resolution and FOV (field of view), which are 640 by 640 and 5 degrees. The important and problematic item is the spectral response of the system. The actual spectral response of a PGP (prism-grating-prism) / camera system such as the SOC-700 is like that shown in Figure 13. There are gaps between the lobes due to the system being based upon a CCD camera. The specified wavelengths for each band after calibration will be the central wavelengths of each lobe. Each SOC-700 system built has a unique spectral response, which is not known until the system is calibrated by Surface Optics.

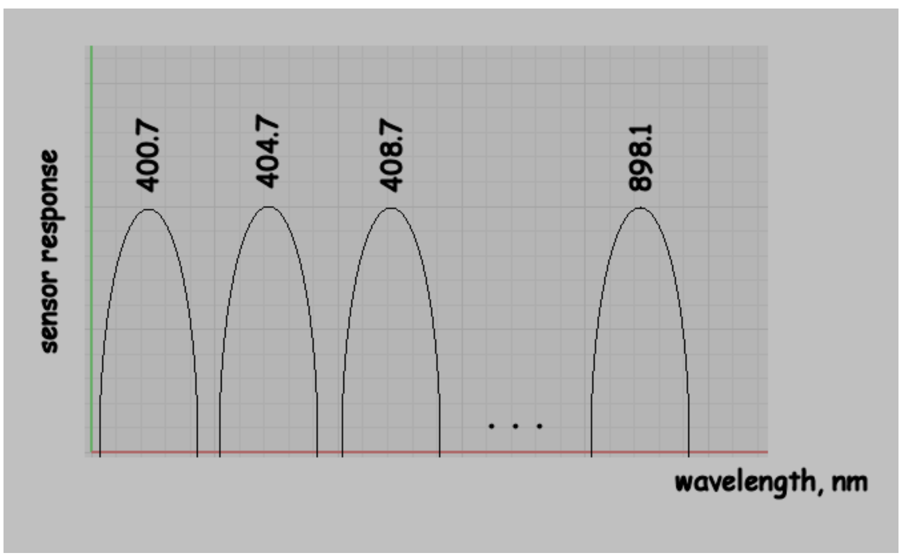

Figure 13 – Theoretical Spectral Response Curves for the SOC-700

Since the SOC-700 is calibrated by the vendor to produce calibrated radiance values, the spectral response function can be considered as spectrally flat. For this modeling effort, a simplified response function was used, with rectangles instead of lobes. This is probably accurate enough for most uses not involving very narrow wavelengths (such as modeling lasers). Custom software was written which created these response rectangles with a 90% spectral fill, with the center wavelengths based upon our SOC-700's wavelengths. These central wavelengths are approximately 4 nm apart, but the exact difference varies over the measurement band due to the calibration process. Figure 14 shows a response function as created and used for this simulation.

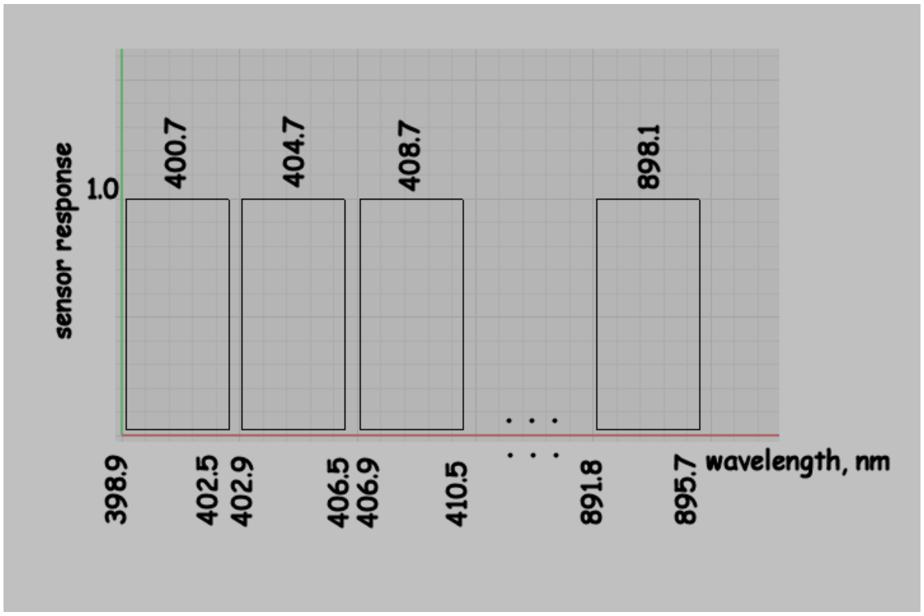

Figure 14 – Approximate SOC-700 Response Function Used for Simulation

CAMEO-SIM also displays the sensor response, shown in Figure 15 and highlighted in red, but with bands this narrow it is difficult to decipher. Checking the data in textual format (Figure 16), verifies that the response function data is correct. Note the small gaps between bands.

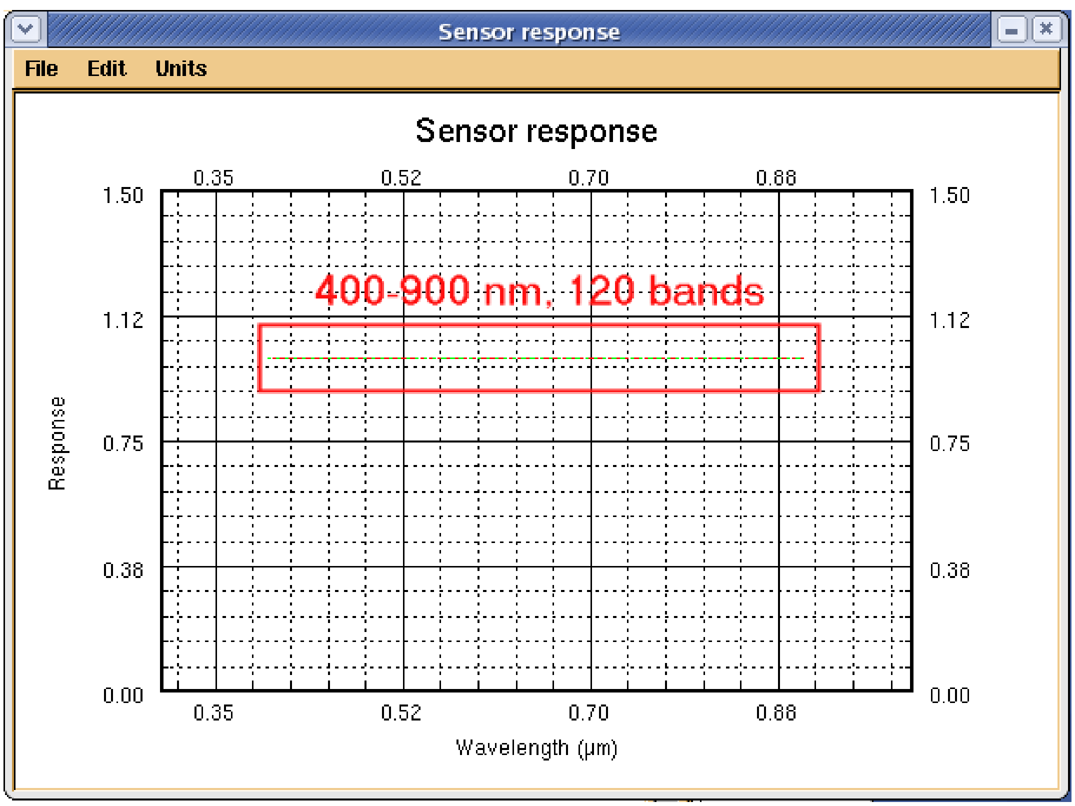

Figure 15 – CAMEO-SIM Display of Hyperspectral Sensor Response (highlighted in red)

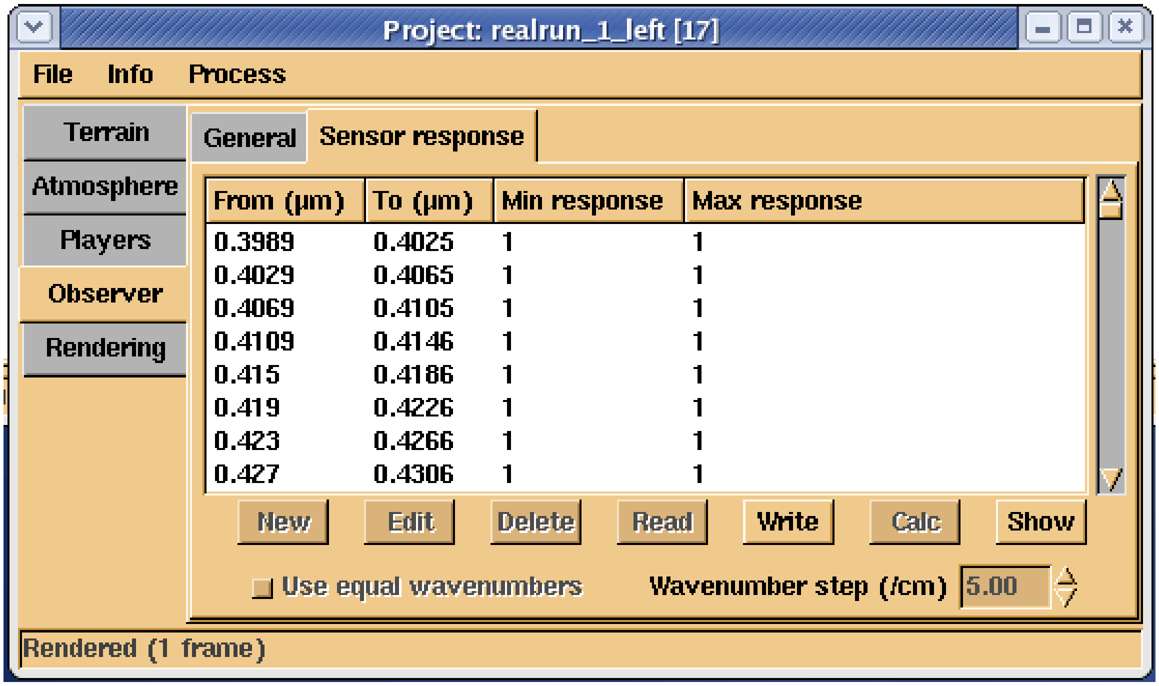

Figure 16 – CAMEO-SIM Text Display of Hyperspectral Sensor Response

One final important CAMEO-SIM setting is to tell it to perform a multispectral simulation, shown in Figure 17. Many other CAMEO-SIM settings are thermal-related, and can be ignored when modeling the visual and near-IR bands.

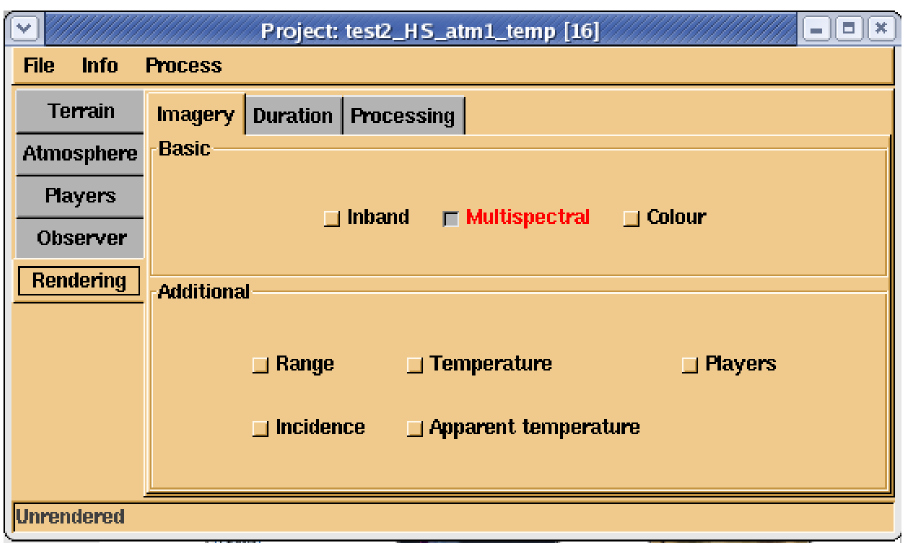

Figure 17 – Multispectral Setting used for SOC-700 Simulation

For this modeling work, the 64-bit version of CAMEO-SIM 5.6 was used, running on 64-bit CentOS Linux 4.3 (a Red Hat derivative). The hardware used has dual 2.4 GHz Opteron processors and 16 GB of memory. Processing one simulated SOC-700 hyperspectral cube takes 1.5 minutes.

RESULTS

The obvious first check is to convert the resulting hyperspectral cubes into color images. Even with the default monitor calibration files applied the results were very satisfying, and showed that the simulation had worked properly, Figure 18. Initially the cement appeared to be a different color in each image, this was due to the auto-gain settings used, along with the lack of a white item in the leaf image. With the brightness levels (i.e. white points) set the same, the cement colors match. It is important to remember that CAMEO-SIM does not directly generate RGB imagery. It generates spectral radiance data, which can be integrated into an RGB image if desired. Most rendering software programs do all of their calculations in the RGB color space, which has no real-world meaning. For example, a spectrometer cannot measure a "percent red reflectance", since "red" has no defined physical meaning. So a spectral radiance cube can be converted into many differing RGB images. CAMEO-SIM supports the use of a monitor calibration file for the most accurate possible image for a given display monitor. Even with this calibration feature, the brightness of the images can be arbitrarily adjusted by the user, since monitors are so limited in dynamic range when compared to the real world.

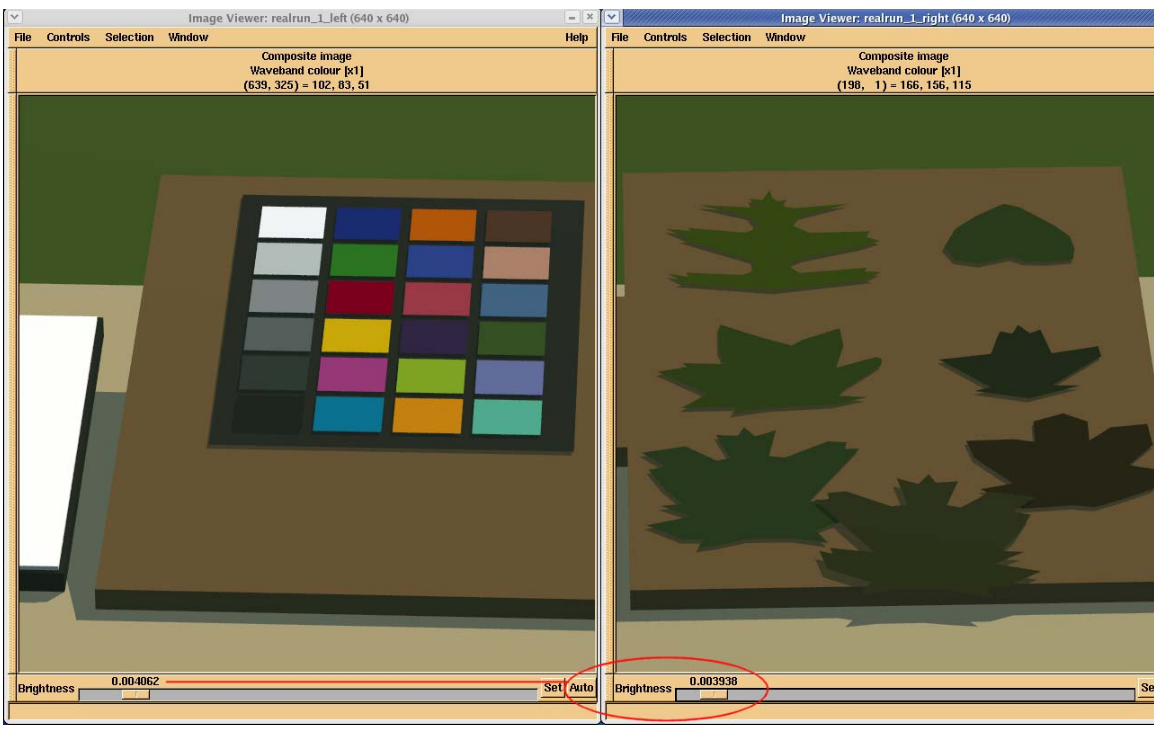

Figure 18 – CAMEO-SIM Results in RGB Color, Adjusted for Equal Brightness

Regardless, the creation of attractive color images was not really the goal here, rather it was the creation of narrowband spectral imagery. So the next test was to compare the images for a given waveband, out of the 120 measured and modeled. Figure 19 shows the first results examined, at 646 nm. The difference in shadow angles was found to be due to United States DST (daylight saving time) being in effect and not accounted for in the CAMEO-SIM simulation. For all later runs one hour was subtracted from the time to fix this. The cement-grass transition at the top of the image also differs, this is a simple geometric issue caused by the lack of a panel-to-grass distance measurement. The Spectralon and the cardboard were both propped up, this distance was measured and built into the geometry. The sensor distance and height were also measured and properly set in the simulation.

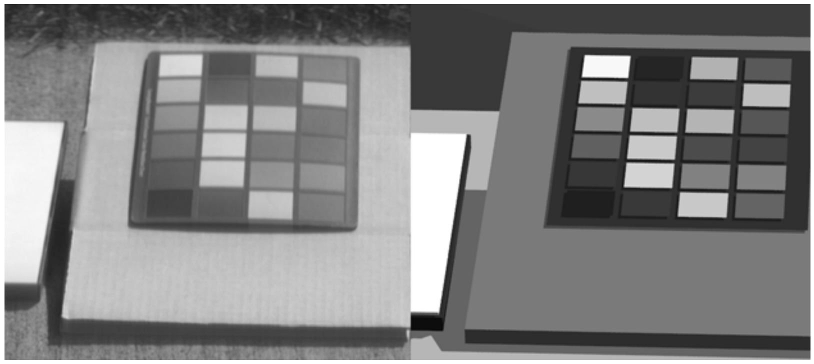

Figure 19 – First Spectral Results, at 646 nm, Modeled Version on the Right, Note the Shadow Angle

Figures 20 - 25 show more narrowband spectral images of the test scenes, the images speak for themselves. The white points of the images compared here are not the same, since there was no intent of generating matching spectral radiance values.

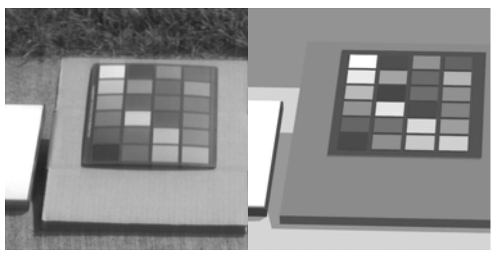

Figure 20 – Charts at 555 nm

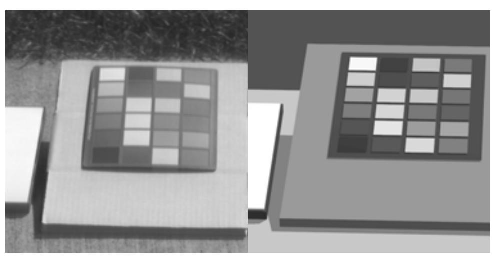

Figure 21 – Charts at 663 nm

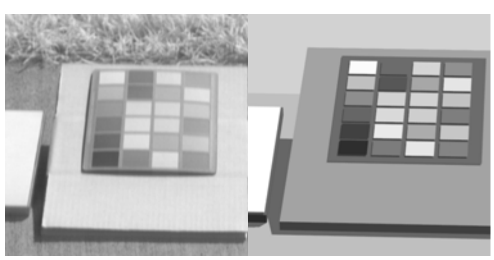

Figure 22 – Charts at 777 nm, Note how Grass is Highly Reflective in the Near-IR Band

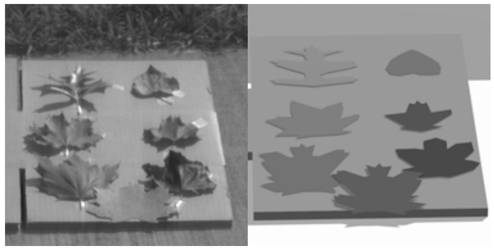

Figure 23 – Leaves at 555 nm

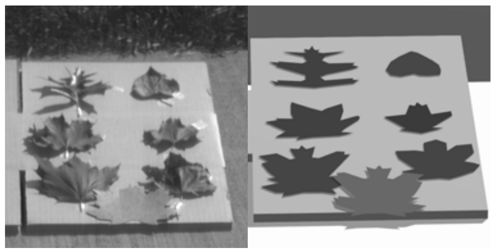

Figure 24 – Leaves at 663 nm

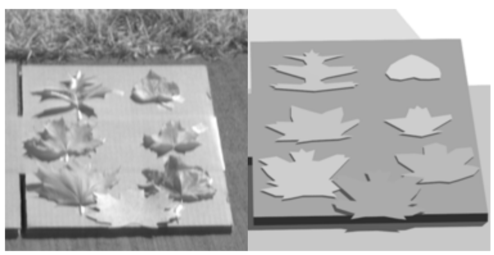

Figure 25 – Leaves at 777 nm

An obvious issue with the real-world leaves is their inability to lie completely flat. This is why the paper leaf at the bottom appears bright at 777 nm in the measured data, even though its spectral reflectance at this wavelength is lower. This in addition to glints off of the glossier leaves makes comparisons more difficult than with the more cooperative color chart. The real world also required pieces of tape to keep the leaves from moving around in the wind. The cement reflectance measurements were probably not very accurate due to the roughness of the cement.

The above observations showed that the spectral simulation using CAMEO-SIM worked well in general, but running some basic hyperspectral analysis algorithms against the data could perhaps give insight into whether this modeled data is useful for simulation purposes. The Surface Optics HS-Analysis software which comes with the SOC-700 system (Figure 26) provides several such algorithms, unfortunately the software only reads in the SOC-700 hyperspectral cube format. Therefore a software program was written to convert the CAMEO-SIM hyperspectral cubes into the SOC-700 format, so that the data could be analyzed with HS-Analysis. This required converting the floating-point spectral radiance values from CAMEO-SIM into 12-bit (0 to 4095) integer count values, and then putting the necessary recalibration values into the SOC-700 file header.

For the particular algorithms implemented in the HS-Analysis 2 software, a target area is drawn on the image and then a spectral difference from that target area is calculated for every pixel in the cube. The exact calculation depends upon the algorithm selected. Two algorithms were applied here – Mahalanobis Distance, and Zero Mean Spectral Area. After the calculations, a threshold slider is moved and each pixel's spectral distance from the target area is determined to either be under the threshold (shown in red), or over the threshold (in black). This interactive type of analysis is difficult to demonstrate with static images. Note that the spectral radiance display in the upper right of Figure 26 shows the averaged target area (lower-left leaf) spectrum in red, and the spectrum of whatever pixel the cursor is on (paper leaf) in black. This graph display reiterates the fact that the simulation is spectral in nature, but note that the graph here displays radiance, not reflectance. The image shows one band (646 nm) out of the 120 modeled, the other bands can be picked from a list.

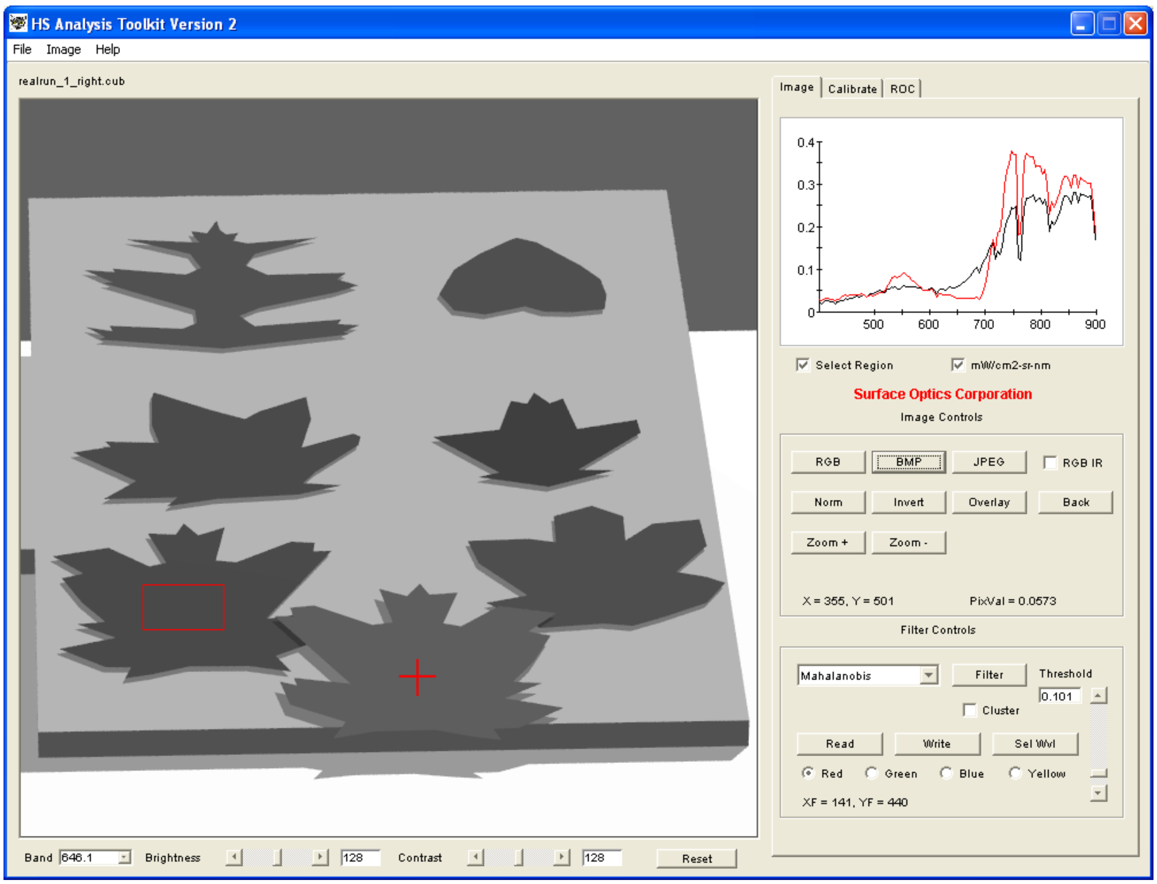

Figure 26 – Surface Optics' HS-Analysis 2 Software with CAMEO-SIM Results Loaded

Performing the Mahalanobis Distance calculation with the Macbeth cubes and the target region set on the yellow sample area of the chart provides different results at the same threshold values (Figure 27 vs. Figure 28). This probably indicates that this algorithm considers brightness to be part of the calculated difference, in addition to the basic spectral shape difference. For the leaf comparison, the lower-left leaf and non-matching threshold values were used, and the match is better (Figure 29 vs. Figure 30).

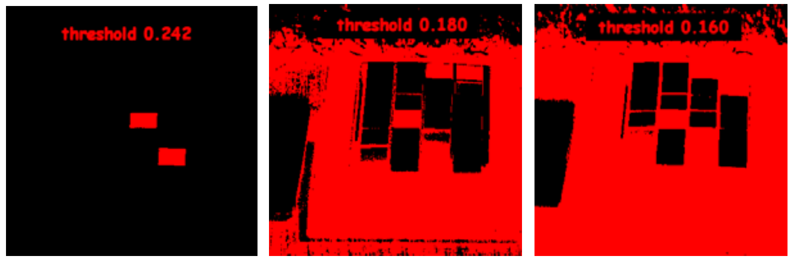

Figure 27 - Mahalanobis Distance, Real Scene, Thresholds of 0.242, 0.180, 0.160

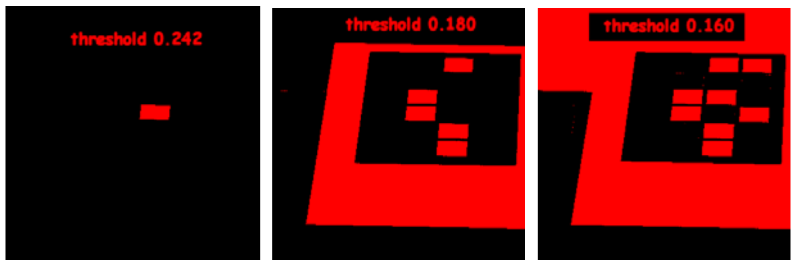

Figure 28 - Mahalanobis Distance, Modeled Scene, Thresholds of 0.242, 0.180, 0.160

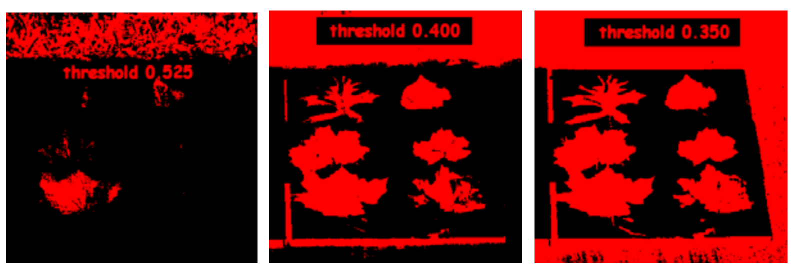

Figure 29 - Mahalanobis Distance, Real Scene, Thresholds of 0.525, 0.400, 0.350

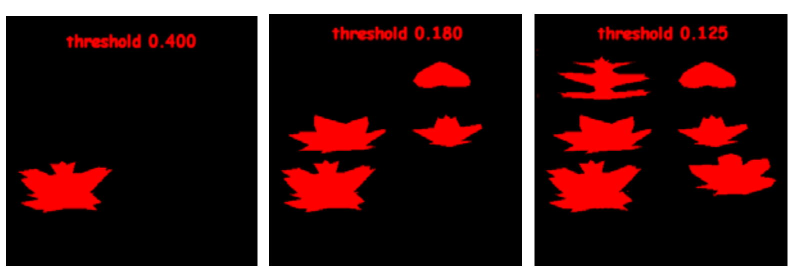

Figure 30 – Mahalanobis Distance, Modeled Scene, Thresholds of 0.400, 0.180, 0.125

"Zero Mean" in the Zero Mean Spectral Angle algorithm name means that each pixel spectrum is normalized before doing any comparisons, so only the spectral shape matters and not the brightness. With this algorithm and the Macbeth chart, with the target area again set on the yellow sample, the match at similar (but not identical) thresholds is excellent (Figures 31 and 32). The match with the leaf cubes is also good, probably hampered by the real leaves not lying flat (Figures 33 and 34). Note that the paper leaf is the last leaf to spectrally match, which makes sense due to its unnatural reflectance spectrum.

Figure 31 – Zero Mean Spectral Angle, Real Scene, Thresholds of 0.900, 0.790, 0.590

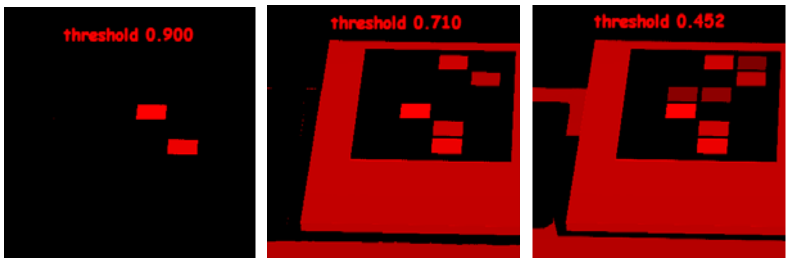

Figure 32 - Zero Mean Spectral Angle, Modeled Scene, Thresholds of 0.900, 0.710, 0.452

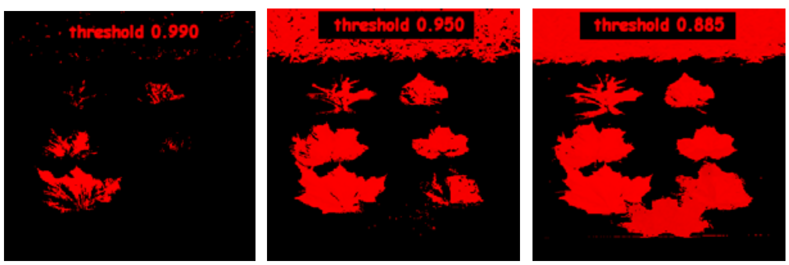

Figure 33 - Zero Mean Spectral Angle, Real Scene, Thresholds of 0.990, 0.950, 0.885

Figure 34 - Zero Mean Spectral Angle, Modeled Scene, Thresholds of 0.990, 0.965, 0.960

Finally, although it was never the intent of this modeling effort to duplicate the measured spectral radiance values of the real-world scene, it is worth comparing the two just out of curiosity. After a minor units conversion, we see that the real and the modeled spectral radiance values coming from the Spectralon sample are at least "in the same ballpark", in Figure 35. This is a better match than expected. One factor making the modeled radiance higher is that the virtual Spectralon was modeled as 100% reflective, whereas our less-clean real Spectralon was found to be about 88% reflective. A good cleaning could probably get it to 94%, but Spectralon only achieves the specified 98% reflectance when brand new and perfectly clean.

There was some cloudiness present on the measurement day, so a measurement 1 minute later could have given completely different radiance values, whether higher or lower. The air pollution found in an urban area is also a significant factor. The smoothness of the SOC-700 data from 400 – 450 nm is probably due to the system's poor response over this spectral region. The spectral radiance dip at about 762 nm is a standard atmospheric absorption feature, and is always observed in outdoor spectral data. Finally, changing the various MODTRAN settings will affect the absolute radiance values calculated for a simulation, as shown earlier.

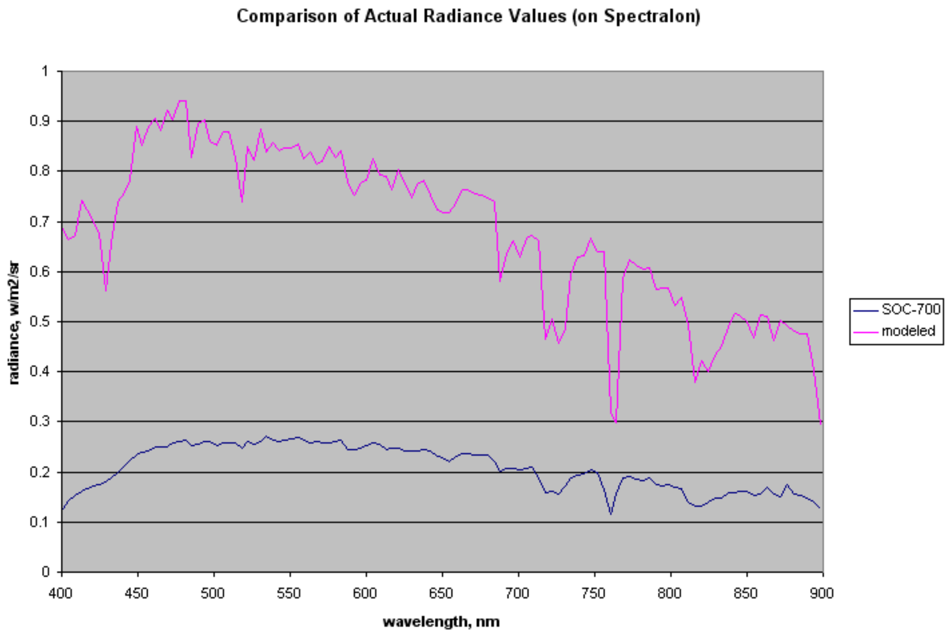

Figure 35 – Comparison of Measured (blue) and Modeled (purple) Spectral Radiance Values in w/m^2/sr

CONCLUSION

CAMEO-SIM has proven to be well-suited for modeling the hyperspectral data cubes produced by the SOC-700 system. In general CAMEO-SIM is easy to use, the only real frustration being the task of setting the material properties for all 30+ materials modeled. The Rhino software works well for creating the necessary object geometries, and the Ocean Optics spectrometer provides appropriate reflectance data for doing SOC-700 simulations. Since CAMEO-SIM was designed to use physically-meaningful values and calculations from beginning to end, the resulting hyperspectral data cubes resulting from the simulation have a very good spectral radiance match with the measured data. Analysis of the real and modeled data with fairly basic hyperspectral algorithms provided similar results.

Future work will investigate using more sophisticated hyperspectral analysis algorithms on the data, such as spectral anomaly detectors. For example a camouflaged item "hiding" in a tree could be both measured and modeled and the detectability metrics compared. The addition of sensor effects such as blur and noise should also be investigated, perhaps using the Compass software available from Insys. The material properties used in the simulation could be made more realistic with the addition of measured BRDF (bidirectional reflectance distribution function) information, which CAMEO-SIM supports.

REFERENCES

[1] Jafolla, James, Hendricks, Leif and Gargadennec, Yannick, 2001, "SOC-700 and HS-Analysis 2 User's Manual", Surface Optics, San Diego

[2] Cohen, Michael F. and Wallace, John R., 1993, "Radiosity and Realistic Image Synthesis", Academic Press, San Francisco

[3] Sillion, Francois X. and Puech, Claude, 1994, "Radiosity and Global Illumination", Morgan Kaufman, San Francisco

[4] Schowengerdt, Robert A., 1997, "Remote Sensing", 2nd edition, Academic Press, San Diego